Mon. Not. R. Astron. Soc. **000**, 1–**??** (2010) Printed 8 April 2010 (MN LaTeX style file v2.2)

The Evolution of Radio Loud Active Galactic Nuclei as a Function of Black Hole Spin

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Released 2010 Xxxxx XX

ABSTRACT
Recent work on the engines of active galactic nuclei jets suggests their power depends strongly and perhaps counter-intuitively on black hole spin. We explore the consequences of this on the radio-loud population of active galactic nuclei and find that the time evolution of the most powerful radio galaxies and radio-loud quasars fits into a picture in which black hole spin varies from retrograde to prograde with respect to the accreting material. Unlike the current view, according to which jet powers decrease in tandem with a global downsizing effect, we argue for a drop in jet power resulting directly from the paucity of retrograde accretion systems at lower redshift z caused by a continuous history of accretion dating back to higher z. In addition, the model provides simple interpretations for the basic spectral features differentiating radio-loud and radio-quiet objects, such as the presence or absence of disk reflection, broadened iron lines and signatures of disk winds. We also briefly describe our models' interpretation of microquasar state transitions. We highlight our result that the most radio-loud and most radio-quiet objects both harbor highly spinning black holes but in retrograde and prograde configurations, respectively.

Key words: Galaxy evolution - black hole spin

1 INTRODUCTION

Over the past decade and a half, our understanding of the dynamics of active galaxies (AGN) has made significant strides. Once of marginal interest astrophysically, black holes have taken center stage, becoming an integral part of galactic dynamics and evolution. The picture that has emerged involves the presence of supermassive black holes at the center of most if not all galaxies, with active galaxies interacting with these black holes via accretion, producing winds and jets. There is overwhelming evidence that galaxies are interconnected with black holes to the extent that the cosmic evolution of both is coupled (Kormendy & Richstone 1995; Magorrian et al 1998; Gebhardt et al 2000; Ferrarese & Merritt 2000; Tremaine et al 2002; Marconi & Hunt 2003). Despite this, there are uncertainties in our understanding of how black hole engines produce jets, how such structures are collimated over large scales, and how galaxies that harbor these powerful engines evolve over cosmic time.

The theoretical framework in which we have attempted to address such questions over the past two decades involves the "spin paradigm" (Blandford 1990; Wilson & Colbert, 1995; Moderski, Sikora & Lasota, 1998), whereby high black hole spin can lead to powerful, radio-loud, jetted AGN, while low black hole spin to radio-quiet, weak or non-jetted AGN where jet power is related to black hole spin via the Blandford-Znajek mechanism (Blandford & Znajek 1977; henceforth BZ). The literature on the BZ effect and black hole spin-related processes for jet formation in relation to radio-loud AGN is extensive. In its most recent guise, the spin paradigm enters the literature in various places and with differing results. Using the BZ mechanism, Mangalam, Gopal-Krishna & Wiita (2009) propose a scenario leading to low black hole spins in advection dominated accretion flows under the assumption that the magnetic flux threading the black hole is insensitive to spin. Similar ideas grounded in general relativistic magnetohydrodynamic simulations suggest that high spin for higher order spin power dependence in thick accretion geometries vs thin accretion flows, produce the conditions for the 3 order of magnitude difference in power between radio-loud and radio-quiet AGN (Tchekhovskoy et al 2010). In work that closely follows the results of numerical simulations that supports the work of Nemmen et al (2007) on high black hole spin in geometrically thick flows, Benson & Babul (2009), also using advection dominated thick accretion flow models, arrive at a maximum spin of 0.92 for black holes, suggesting that a spin-equilibrium scenario is compatible with the linear accretion rate dependence of jet power found in recent observations of AGN jets (Allen et al 2006).

In addition to the question of the radio-loud/radio-quiet division in active galaxies, a division within the group of jetted AGN is

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observed and a classification is produced according to differences in power and jet collimation (Fanaroff & Riley 1974). Attempts at understanding this Fanaroff-Riley (FR) division have also been framed in the context of the spin-paradigm in an attempt to explore the possibility of differences in spin between FRII and FRI objects. Meier (1999) suggested a magnetic switch operating at high spin triggers the production of relativistic jets. Using the BZ effect and hybrid Meier model, Daly (2009b) calculated the cosmological evolution of black hole spins, showing that they are largest (about unity) for the FRII sources at high redshift and decrease (to about 0.7) for radio-loud sources at lower redshift. The idea that the engine of jets determines their FR morphology spans the works from Rees (1982) to Hardcastle et al (2007). A theoretical approach to determining black hole spin that is model-independent, but assumes that spin changes only by extraction of the reducible black hole mass, applied to a small subset of powerful radio galaxies, finds that they harbor low spinning black holes (Daly 2009a). This work suggests also that the FRI/FRII division is due to environment. Such environmental effects on jet morphology, unrelated at least directly to the properties of the central engine of the jet, have been addressed starting with De Young (1993) and more recently with Gopal-Krishna and Wiita (2000). Black hole mass dependence (Ghisellini & Celotti 2001) and accretion dependence of the FRI/FRII division have also been explored (Marchesini et al 2004).

Under the assumption that jets are produced by the combined effort of the BZ and Blandford-Payne (Blandford & Payne 1982; henceforth BP) effects, recent numerical studies of general relativistic magnetohydrodynamics of black hole accretion flows suggest a tight link between jet power and black hole spin (Garofalo, 2009a, 2009b). Whereas BZ involves jets produced via spin-energy extraction from the black hole, BP is a jet mechanism that originates in the accretion disk via mass-loading of disk gas onto large scale magnetic fields. The black hole spin dependencies of these processes have direct implications for the jets produced in AGN. According to these studies, largest BZ power occurs for highly retrograde accretion systems with respect to the black hole and less so for prograde ones, transitioning to zero power at zero spin while the BP power is also maximized for highly retrograde accretion but monotonically decreases toward high prograde ones.

In the context of this framework, we attempt in this paper to construct a physical foundation for the morphology and evolution of jet-producing AGN. At the heart of our picture lies the notion that accretion onto spinning supermassive black holes tends, in time, to produce increasingly prograde accretion systems, in which lower jet output is hosted by more stable accretion configurations. In terms of the radio-loud AGN population, "high excitation radio galaxies", evolve over cosmic timescales toward "low-excitation radio galaxies", as black holes conspire with their host galaxy in evolving toward prograde accretion states from an earlier phase of retrograde accretion flow. In addition, we suggest a retrograde vs prograde division for the engines of radio-loud objects whose interaction with the external environment produces the distribution of the Fanaroff & Riley classification, according to which the powerful, highly collimated jets of the FRII class, are retrograde spin systems while the mostly less powerful, less collimated FRI sources embedded in gas-rich environments are the late-state evolution toward prograde accretion systems. Our interpretation of the radio-loud/radio-quiet division will be that the most radio-loud and the most radio-quiet AGN both harbor rapidly rotating black holes with their accretion angular momentum vectors determining the difference, while the FRI/FRII division in our model is based on a combination of nuclear properties and environment. In addition to this, our model unifies radio-loud, radio-quiet, and FRI, FRII objects, to the extent, as we will illustrate, that radio-loud objects of the FRII class evolve either into radio-loud FRI objects or into radio-quiet AGN. We point out, furthermore, that the theoretical frameworks grounded in the spin-paradigm discussed above, all suffer from a "spin paradox" (David L. Meier) to be discussed in a follow-up paper in which we illustrate its resolution within our framework (Meier & Garofalo, in preparation). In section 2 we highlight the relevant observed properties of radio-loud AGN which constitute the pieces of the theoretical puzzle we construct in Section 3. Section 4 briefly addresses the radio-loud/radio-quiet dichotomy in this model and its extension to microquasars and then concludes.

2 RADIO-LOUD AGN: OBSERVATIONAL PICTURE

In this section we emphasize the main observational features concerning the radio-loud population and give a broad-brush description of past attempts and difficulties in combining such features into a theoretical framework.

2.1 The Excitation Dichotomy in Radio-Loud AGN

Extensive optical and X-ray surveys show clear evidence for a fundamental dichotomy in the properties of radio-loud AGN, which is directly related to the mode of accretion onto the central supermassive black hole.

"High-excitation radio galaxies" (HERGs), those with prominent emission lines in their optical spectra, have standard, geometrically thin accretion disks and accrete at a significant fraction of their Eddington limits. These sources are heavily obscured in the X-ray by columns in excess of 10^{23} cm^{-2}, consistent with AGN unification (Donato et al. 2004; Evans et al. 2006). HERGs show weaker, if any, neutral, inner-disk, broadened Compton reflection continuua compared to radio-quiet AGN (Reeves & Turner 2000; Grandi et al. 2002). Furthermore, most of these sources have narrow, typically unresolved neutral Fe Kα lines (Evans et al. 2004, 2006), which indicates that the primary X-ray emission is being reprocessed far from the inner disk regions. HERGs tend to inhabit isolated environments, at least at low redshift, and often show evidence for recent mergers, consistent with the idea that they derive their power from the accretion of cold gas (Hardcastle, Evans, & Croston 2007). *Spitzer* IRS spectroscopy (Ogle et al. 2006) shows that HERGs are luminous MIR emitters, and the detection of strong 9.4μm silicate absorption implies that they possess molecular tori.

On the other hand, "low-excitation radio galaxies" (LERGs) – those with few or no observed optical emission lines – lack any of the features required by standard AGN unification models. Their X-ray emission is dominated by a parsec scale jet, they have radiatively inefficient accretion flows ($L/L_{Edd} \sim 10^{-(5-7)}$ - where L is luminosity and L_{Edd} is the Eddington luminosity), and they show no evidence at all for an obscuring torus (Hardcastle, Evans, & Croston 2006; Ogle et al 2006). These sources tend to inhabit hot, gas-rich environments, such as groups and clusters. It has been suggested by Hardcastle, Evans, & Croston (2007) that the jet outbursts in LERGs derive their power from the Bondi accretion of this IGM/ICM gas. This result holds for the majority of LERGs, but cannot be applied to the most powerful jets in clusters of galaxies, such as MS0735.6+7421 (McNamara et al. 2009), whose kinetic power exceeds that available from Bondi accretion.

Finally, while LERGs show no evidence of ionized outflows

	Low-excitation (LERG)	High-excitation (HERG)
Definition	No narrow optical line emission.	Prominent optical emission lines, either narrow (NLRG) or broad (BLRG), or quasar.
Fanaroff-Riley classification	Almost all FRIs are LERGs at z=0. Significant population of FRIIs at z ∼0.5.	Most FRIIs are HERGs, as are a handful of FRIs (e.g., Cen A).
X-ray spectra	Jet-related unabsorbed power law only. Upper limits only to 'hidden' accretion-related emission.	Jet-related unabsorbed power law + significant accretion contribution (heavily absorbed in NLRGs).
Accretion-flow type	Highly sub-Eddington. Likely radiatively inefficient.	Reasonable fraction of Eddington. Likely standard accretion disk.
Optical constraints	Strong radio/optical/soft X-ray correlations. Optical emission is jet-related.	Strong radio/optical/soft X-ray correlations. Optical emission is jet-related.

Table 1. Overview of the properties of low- and high-excitation radio galaxies

of gas or winds from their central regions, evidence is emerging for such outflows in HERGs, at least in X-rays (Reeves et al 2009; Tombesi et al submitted), although less so than for their radio-quiet counterparts.

2.2 The Fanaroff-Riley Dichotomy in LERGs and HERGs and its Redshift Dependence

HERGs and LERGs can be further classified according to whether they belong to the Fanaroff & Riley classification FRI or FRII (Fanaroff & Riley 1974), whose differences are related to the power of the jet and the physics of mass-loading (entrainment). FRI-type radio galaxies display "edge-darkened" radio morphology, with generally weak jets that are poorly collimated on kpc-scales. FRIIs are typically more powerful and more collimated. Whereas most FRIIs are HERGs and most FRIs are LERGs, *Chandra* observations indicate the existence of mixed FRII LERG and FRI HERG states. FRI HERGs are very rare. One example is the nearest AGN, Centaurus A (Evans et al. 2004). On the other hand, there is a significant population of FRII LERGs, which occur at what is arguably an intermediate redshift ($z = 0.5 - 1$) for these objects, and essentially zero cases at low redshift ($z < 0.1$). FRII LERGs tend to lie in gas-rich groups or cluster-scale environments.

The appearance of radio-loudness in the forms discussed above and the connection to radio-quiet AGN forms the subject of the following sections. Combinations of radiatively inefficient/efficient accretion flow with high/low spinning black holes (the spin paradigm) are only partially successful in modeling the observations. The observed weakness of disk winds and broadened reflection features in FRII HERGs compared to radio-quiet objects remains unexplained. Recent work points to a possible resolution of such problems by suggesting that radiative efficiency in very high accretion rate systems may be accompanied by fully ionized inner regions, thereby explaining the weakness of the reflection component (Sambruna et al 2009 and references therein). Explaining LERG jet systems in gas-rich clusters and the energetics of the FRII class is also problematic as mentioned above. For LERG jets, the observed linear relation between jet power and accretion power (Allen et al 2006) is expected assuming the BZ effect is operating but energetically can only be explained if the black holes are maximally spinning (Nemmen et al 2007; Benson & Babul 2009), which, in turn, implies there is fine-tuning in the spin parameter. The attempt to extend this linear relation between BZ jet power and accretion rate fails for the FRIIs because the observed accretion power is too weak. And finally, models suggesting high spin leads to powerful jets are statistically incompatible with mounting evidence for high-spinning black holes in Seyfert galaxies as it becomes problematic to assume such objects are all currently living within their radio-quiet phase (Wilms et al 2001; Brenneman & Reynolds 2006; Fabian et al 2009; Zoghbi et al 2010).

In the next section we attempt to produce a black hole engine-based theoretical framework that addresses these observed properties. We will argue that misaligned, or retrograde systems, in which disk gas rotates opposite to that of the black hole, create the conditions for powerful jets albeit in dynamically unstable configurations, whose time evolution is toward energetically more stable conditions in which the black hole and disk coexist in rotationally aligned states. We will suggest that in addition to radiative efficiency or lack thereof and black hole spin, alignment vs misalignment between the angular momentum of the black hole and the disk, is crucial.

3 RADIO LOUD AGN: THEORETICAL FRAMEWORK

In this section we describe the theoretical framework within which we fit the observational elements of the previous section. The fundamental distinguishing feature of the theory (Garofalo, 2009a) involves the change in size of the gap region that exists between the inner edge of accretion disks located near the innermost stable circular orbit (ISCO) and the black hole horizon. The size of the gap region changes as a function of black hole spin because the ISCO depends on spin. We quantitatively determine the effect that the change in size of the gap region has on the BZ mechanism, on the BP mechanism, and on the overall effect of the gap region on jet power and collimation under the assumption that BZ and BP are the dominant and mutually dependent mechanisms involved in jet production. Finally, we include the effect of the gap region on accretion efficiency. We should emphasize that the fundamental feature of our model involves the inverse relationship between accretion efficiency and jet efficiency, and that section 3.2 is focused on illustrating the dependence of such efficiencies on the size of the gap region.

3.1 BZ and BP: quantitative approach

We assume the spacetime is that of a rotating black hole and proceed in Boyer-Lindquist coordinates for which the Kerr metric takes the form,

$$dS^2 = -\left(1-\frac{2Mr}{\rho^2}\right)dt^2 - \frac{4Mar\sin^2\theta}{\rho^2}dt\,d\phi + \frac{\Sigma}{\rho^2}\sin^2\theta\,d\phi^2 + \frac{\rho^2}{\Delta}dr^2 + \rho^2 d\theta^2, \quad (1)$$

where M is black hole mass, a is the dimensionless spin parameter,

$$\rho^2 = r^2 + a^2\cos^2\theta, \quad (2)$$

$$\Delta = r^2 - 2Mr + a^2, \quad (3)$$

and

$$\Sigma = (r^2+a^2)^2 - a^2\Delta\sin^2\theta. \quad (4)$$

The basic equation describing the evolution of the large-scale magnetic field within a Novikov & Thorne (1973) acccretion disk is obtained by following the relativistic analogue (Garofalo 2009b) of the non-relativistic treatment of Reynolds et al (2006), by combining Maxwell's equation

$$\nabla_b F^{ab} = \mu J^a, \quad (5)$$

with a simplified Ohm's law

$$J^a = \sigma F^{ab}u_b, \quad (6)$$

where F^{ab} is the standard Faraday tensor, μ is the permeability of the plasma, J^a the 4-current, u^a the 4-velocity of the accretion disk flow, and σ the effective conductivity of the turbulent plasma. This gives

$$\nabla_b F^{ab} = \frac{1}{\eta}F^{ab}u_b, \quad (7)$$

where $\eta = 1/\mu\sigma$ is the effective magnetic diffusivity. The equations are cast in terms of the vector potential, which is related to the Faraday tensor via

$$F_{ab} = A_{b,a} - A_{a,b}, \quad (8)$$

and, in particular, in terms of the component A_ϕ in the coordinate basis of the Boyer-Lindquist coordinates.

Ultimately, to examine BZ and BP powers, we need to derive the magnetic flux and angle of the flux contours threading a hoop placed at a given radius r. The magnetic flux function is related to the vector potential via Stokes' Theorem applied to the Faraday tensor

$$\psi \equiv \int_S F = \int_S dA = \int_{\partial S} A = 2\pi A_\phi, \quad (9)$$

where S is a space-like surface with boundary ∂S consisting of a ring defined by $r = \text{constant}$, $\theta = \text{constant}$, and $t = \text{constant}$. Since A_b is specified up to the gradient of a scalar function Γ,

$$A_b^{'} = A_b + \nabla_b\Gamma, \quad (10)$$

the assumption of time-independence and axisymmetry gives us

$$A_t^{'} = A_t \quad (11)$$

and

$$A_\phi^{'} = A_\phi. \quad (12)$$

Thus, we need not specify the gauge uniquely beyond the statement of t and ϕ independence.

The region outside the black hole and accretion disk is modeled as force-free, satisfying

$$F^{ab}J_b = 0 \quad (13)$$

and

$$\nabla_b F^{ab} = \mu J^a. \quad (14)$$

Outside the accretion disk we also impose the ideal MHD condition

$$F^{ab}u_b = 0, \quad (15)$$

where u^b is the 4-velocity of the (tenuous) plasma in the magnetosphere and is determined by the condition that field lines rigidly rotate. The numerical details can be found in Garofalo 2009b.

We now consider the BZ and BP powers that result from the numerical solution of the above equations under the assumption that the gap region is not threaded by magnetic flux (i.e. the Reynolds conjecture of a zero-flux boundary condition - Reynolds et al 2006; Garofalo 2009b), where this ability of the gap region to enhance magnetic flux on the black hole is supported also by general relativistic MHD simulations (McKinney & Gammie, 2004). The foundation of the Reynolds conjecture stems from noting that within the gap region, circular orbits are no longer stable and the accretion flow plunges into the black hole. In Reynolds et al (2006), it is argued that the inertial forces within the gap region prevent magnetic flux that is threading the black hole from expanding back into the disk. Accretion of magnetic field can result in a strong flux-bundle threading the black hole, confined in the disk plane by the gap region. We start by evaluating the horizon-threading magnetic field as measured by ZAMO observers from the flux values we obtain,

$$B_H = \sqrt{g_{11}}B^r \quad (16)$$

with

$$B^r = *F^{rb}u_b, \quad (17)$$

where $*F^{ab}$ is the dual Faraday tensor and u^b is the four-velocity of the ZAMO observers evaluated in the equatorial plane on the stretched horizon or membrane in the sense of the Membrane Paradigm (Thorne et al 1986), and from this magnetic field value we determine BZ power as (Thorne et al 1986),

$$L_{BZ} = 2\times 10^{47} ergs\ s^{-1}(\frac{B_H}{10^5 G})^2 m_9^2 j^2 \quad (18)$$

where B_H is the poloidal magnetic field threading the black hole, j is the normalized angular momentum of the black hole or a/M, and m_9 is the black hole mass in units of 10^9 solar masses.

BP power is similarly constructed but depends on magnetic field strength threading the accretion disk, the bend angle with which the magnetic field presents itself to the disk surface, or more precisely, the radial extent over which the bend angle is sufficient for mass-loading, and the Keplerian rotation rate which is also spin-dependent. Following Cao (2003) we have

$$L_{BP} = \int B_d^2 r^2 \Omega dr \quad (19)$$

where B_d is the field strength threading the disk and Ω is the rotation of the disk magnetic field. The radial extent over which

the bend angle is large enough for mass-loading, increases with increase of spin in the retrograde regime and comes from the numerical solution (Garofalo 2009b). We show the power in BZ in Figure 1, that in BP in Figure 2 and the overall power in Figure 3 assuming they combine as follows, where the functions α and β capture the effects on BP and BZ powers from the numerical solution in the context of the Reynolds conjecture (Garofalo 2009b).

$$L_{jet} = 2 \times 10^{47} ergs\ s^{-1} \alpha \beta^2 (\frac{B_d}{10^5 G})^2 m_9^2 j^2 \tag{20}$$

where

$$\alpha = \delta(\frac{3}{2} - j) \tag{21}$$

and

$$\beta = -\frac{3}{2}j^3 + 12j^2 - 10j + 7 - \frac{0.002}{(j-0.65)^2} + \frac{0.1}{(j+0.95)} + \frac{0.002}{(j-0.055)^2}. \tag{22}$$

While j spans negative values for retrograde spin and positive values for prograde spin, a conservative value for δ of about 2.5 is adopted but our ignorance of how jets couple the BZ and BP components restrict our ability to specify it and suggest that it might well be larger by an order of magnitude or more.

While α can be thought of as the parameter that determines the effectiveness of the BP jet as a function of spin, β captures the enhancement on the black hole of the disk-threading field, both within the context of the Reynolds conjecture. The parameter δ determines the effective contribution of BP to overall jet power, with larger values shifting jet power efficiency more toward the retrograde regime. Because, as we point out in the next section, our focus is on the collimating properties of BP jets, we have been conservative in choosing a small δ of order unity. It is important to point out that the no-flux boundary condition's effect is to increase the BZ and BP efficiency toward the retrograde regime. The consequence of this for prograde spin is to produce a flattening of the overall jet power so that low prograde black hole spins have powers that increase. The behavior of the power in Figure 3 follows from the assumption of a force-free magnetosphere but changes if this assumption is relaxed. A non-negligible inertia for fast rotating magnetospheres and the added centrifugal barrier that would ensue, would make it more difficult for plasma to be advected inward through the diffusionless gap region, a situation that arises more for the high prograde regime as the rotation is greater. As a result, a more realistic magnetosphere should further shift the overall jet power efficiency toward the retrograde regime, thereby further flattening the spin dependence in the prograde one.

3.2 Jets vs. accretion: the gap paradigm

We combine these results and produce the following illustration of the combined effect of BZ and BP on jet power and collimation.

(i) In the left column in Figure 4 we show the difference between accretion systems around spinning black holes as a function of the spin parameter and type of accretion (i.e. prograde vs. retrograde) and its effect on the BZ power. We use negative spin values to indicate retrograde accretion while positive spin values indicate prograde accretion. Note how the gap region is larger as the spin increases from large prograde to large retrograde. The shrinking of the gap region in the prograde direction, produces an asymmetry in BZ power that favors retrograde systems. As a result, retrograde BZ power is larger as indicated by the length of the arrows. The basic physics behind this power dependence on spin is that larger gap region allows greater magnetic flux accumulation on the black hole (Garofalo, 2009b).

(ii) In the center column of Figure 4 we present a schematic of the monotonic dependence of BP on spin by using arrows that originate in the disk (since BP jets are disk-launched). The length again indicates the magnitude of the jet and we highlight how the power increases from high prograde to high retrograde. Here, as well, the size of the gap region is instrumental in that larger gap regions produce greater magnetic flux on the black hole, which leads to greater bending of inner-disk-threading magnetic field lines, which, in turn, leads to greater mass outflow and more effective BP jets (Garofalo 2009a).

(iii) By considering both the left and central columns of Figure 4 we combine the effects and produce an overall picture for the jets in retrograde vs prograde black hole accretion systems. Assuming that BP jets originating in the disk/corona are essential for jet collimation (McKinney & Narayan 2007; Bogovalov & Tsinganos 2005; Meier et al 2001), and that such collimation is directly related to jet acceleration (Tchekhovskoy, McKinney & Narayan, 2009), the strongest and most collimated jets occur for high retrograde systems while high prograde systems produce low-power, weakly collimated jets due to the weakness of BP, despite the presence of strong BZ. Our heuristic, qualitative scenario proposes that the jet itself comes from the BP effect but is sparked, in some sense, by the BZ mechanism. It is worth pointing out that we are not illustrating a precise mechanism for producing jets, but simply highlighting the compatibility that arises between theory and observation if BP and BZ conspire as described above. In addition, surviving MHD disruptions such as the kink mode instability (Nakamura & Meier 2004), appears to occur in combination with the presence of a disk jet and relativistic bulk motion (Hardee & Hughes, 2003; McKinney & Blandford, 2009) The diagram, therefore, illustrates these ideas with uncollimated jets for the high prograde case resulting from small BP, no jet in the zero spin case, and a powerful, collimated jet for the high retrograde case resulting from strong BP.

We highlight two aspects of the BZ/BP scenario. The first is that whereas jet power displays a roughly flat spin dependence for a range of prograde spin values, this does not occur for retrograde spin. This indicates that unlike for retrograde spins, there is a range of prograde spin values for which jet power is weakly dependent on spin. We also re-emphasize the fact that BP jets do not simply add to the overall jet power according to our picture; they serve the fundamental purpose of collimation (a feature motivated in the diagrams of Figure 4).

In addition to the effect that the location of the disk inner edge has on jet production, the size of the gap region is also connected to the energetics of the disk itself. Recent work extending standard, radiatively efficient accretion disk theory to self-consistently include the effects of magnetized coronae and disk winds, shows that larger gap regions inhibit or limit the presence of disk winds (Kuncic & Bicknell 2004, 2007). The further out in radial position for the disk inner edge, the less gravitational power is available to be reprocessed in the disk to produce mass outflows further out in the disk. This is illustrated in the right column of Figure 4. With only these considerations on the spin-dependent size of the gap region, we introduce the predictions of our model for the cosmological evolution of AGN (S.3.3), and its implications for the Fanaroff-Riley

dichotomy (S.3.4) and the observed X-ray characteristics of radio-loud AGN (S.3.5).

3.3 Cosmological Evolution of Radio-Loud AGN

Our story focuses on the fraction of objects that involve retrograde accretion onto rapidly spinning black holes, most likely formed in mergers of equal mass black holes or in mergers of black holes where the larger one spins rapidly and the merger with the smaller one is in the prograde direction (Hughes & Blandford 2003). As long as the angular momenta of the disk, J_d, and that of the black hole, J_h, satisfy

$$cos\theta < -\frac{J_d}{2J_h}, \tag{23}$$

where θ is the angle between the two angular momentum vectors (King et al. 2005), counteralignment between disk and black hole occurs (i.e. $\theta = \pi$) and a retrograde accretion state is formed. Because the merger produces a gas-rich environment mainly in the form of cool, molecular gas, that feeds the black hole at relatively high accretion rates (Barnes & Hernquist 1991), we associate this initial phase with HERGs. In other words, the relatively high accretion rates are such that the accretion flow is close to a standard, radiatively efficient Novikov & Thorne disk. The powerful, highly collimated jet, on the other hand, is a direct consequence of the fact that the system is in a highly retrograde accretion state (i.e. the black hole engine is operating at maximum efficiency due to the presence of strongest BZ and BP effects). In other words, these FRII HERGs are powered by nuclear engines in the lower panel of Figure 4.

We now consider the evolutionary paths of two initial FRII HERGs whose jet powers differ, due perhaps to different ratios of black hole mass to the amount of post-merger cold gas. Recent work indicates that high redshift, $z \sim 2$, radio-loud quasars, can deliver $\sim 10\%$ of the jet energy to the ISM, sufficient to expel the cold gas via outflows up to 1000 km/s in $\sim 10^7 yrs$. (Nesvadba et al. 2008). If the loss of cold gas due to this radio-mode AGN feedback leads to a drop in the pressure and density of the ISM, it is expected that accretion will switch to hot Bondi-fed advection-dominated accretion flow (ADAF - Narayan & Yi 1995) from cold, thin-disk accretion at higher redshift as galaxies expand to ~ 3 times their size (Mangalam, Gopal-Krishna & Wiita 2009 and possibly as envisioned in Antonuccio-Delogu & Silk 2010). If the initial FRII HERG is of lower jet power (Fig. 5), the expulsion of cold gas is less effective, and the transition to hot Bondi-fed ADAF accretion is slower. In this case, the initial FRII HERG transitions to an FRI HERG. The FRI nature of the system originates in the fact of prograde accretion as mentioned in the Introduction, while the HERG label corresponds to the relatively high accretion rate and thus to radiatively efficient accretion flow. In other words, the spin-up toward the prograde direction occurs faster than the transition from radiatively efficient accretion to ADAF accretion.

If, on the other hand, the initial FRII HERG jet is more powerful and more effective in expelling the cold gas, the initial FRII HERG transitions to an FRII LERG, due to the fact that the system remains retrograde but the accreting gas is now hot and enters the ADAF phase (i.e. the black hole has not accreted enough to have been spun down and then up again in the prograde regime-Fig. 6).

There are two basic processes working together here. The first involves accretion feeding a black hole in a retrograde state. *Continued accretion initially spins the black hole down toward zero spin and then up again in a prograde state where the angular momentum vector of the black hole is parallel to that of the accretion flow.* The other process involves the accretion state itself. If the accreting gas is cold, the accretion flow radiates in an efficient manner. However, as described, the FRII HERG jets expel cold gas and the timescales on which they accomplish this depends on jet power. Therefore, more or less powerful FRII HERG, cold gas-expelling jets, create the conditions that produce a mixing of FRIIs and FRIs with the HERG and LERG states. Nevertheless, continued cosmological evolution of both FRII LERGs and FRI HERGs inevitably leads toward FRI LERG states, so the mixed states appear at intermediate redshifts as is observed (Hardcastle, Evans & Croston, 2006). In other words, the appearance of these transitional states between FRIIs and FRIs is observationally in agreement with our model in that mixed states are sandwiched between FRII HERGs and FRI LERGs. From a general perspective, cosmological evolution in this model produces FRI LERGs from FRII HERGs. As a direct consequence of this, LERGs have higher black hole masses than HERGs, as is observed (Smolcic et al. 2009; Smolcic 2009).

The boundary between FRIIs and FRIs produces other interesting morphologies. As a consequence of the fact that BZ power drops to zero at zero black hole spin, there must be a transition period in which the jet engine turns off. The timescale of this transition depends on the accretion rate so our emphasis remains qualitative, but we could imagine the following scenario. Because the transition involves going from an FRII to an FRI state, a jet morphology might appear in which further away from the black hole engine is the presence of the relic, well-collimated FRII double-sided jet, whereas closer to the black hole appears the younger double-sided FRI jet, such as in 3C 288 (Bridle et al. 1989; Lal et al. in preparation). Alternatively, the likelihood is that of a spin-flip without transition through zero spin. The spin value of that flip would produce an even larger break in the boundary between FRIIs and FRIs. This transition or gap in the efficiency of the engine near zero spin or due to a spin-flip is important in that it provides the possibility of a sharp break between states that have high and low BP, suggesting a natural location for a break between collimated and uncollimated or less collimated jets.

We also emphasize the fact that our model is founded on the prescription of prolonged accretion as opposed to chaotic accretion scenarios (Volonteri, Sikora & Lasota 2007; Berti & Volonteri 2008; King, Pringle & Hoffman 2008) so that most of the mass is provided by an accretion disk with fixed orientation (Miller 2002), and thus, as pointed out in more detail in the discussion section, we expect black holes in all galaxies to evolve toward highly spinning prograde values as a result. The chaotic accretion scenario is usually invoked to produce low spins in radio-quiet spiral galaxies under the assumption that the spin paradigm operates; but, given that radio-quiet AGN are not low-spinning black hole accretion systems in the gap paradigm, no such mechanism need be invoked (as pointed out by Berti & Volonteri (2008), the spin of 0.99 claimed by Brenneman & Reynolds for MCG-06-30-15, is very unlikely in the chaotic accretion scenario.) In other words, *accretion in the gap paradigm simply spins all black holes up in the prograde direction in all galaxies, ellipticals as well as spirals*. Accordingly, the observed distribution of powerful radio-loud galaxies reflects the ability of mergers to produce retrograde accretion flows in our model, which implies that mergers are constrained to produce a peak of such occurrences at $z \approx 2$, a distribution that dies off at higher and lower z.

3.4 FRI/II Dichotomy

The FRI/FRII dichotomy between low radio-luminosity, poorly collimated radio jets and high radio-luminosity, highly collimated radio jets, has been explained according to two different physical scenarios. The first assumes that external environmental factors influence the jet structure (De Young 1993; Laing 1994; Bicknell 1995; Kaiser & Alexander 1997; Gopal-Krishna & Wiita 2000), while the second attributes the differences in morphology to parameters associated with the jet production mechanism itself (Rees 1982; Baum et al 1995; Reynolds et al 1996; Meier 1999, 2001; Ghisellini & Celotti 2001; Marchesini et al. 2004).

Our model weighs in on this issue by naturally reproducing an FRI/FRII, Ledlow-Owen-like diagram as we illustrate below. Figure 3 shows the power in the jet as a function of spin state. According to our scenario, FRIIs are retrograde accretion systems and so are located on the left side of the break centered at zero spin. FRIs, instead, are modeled as prograde spin states so are located on the right-hand-side of the break. The time flow in our model runs from retrograde accretion toward prograde accretion. Therefore, the x-axis can be replaced by time. Such a jet power vs time diagram serves the purpose of illustrating the cosmological evolution of a single initial FRII HERG. In attempting to recover a Ledlow-Owen-like diagram from our model, we must consider a combination of the time evolution of multiple initial FRII HERGs. The simplest way to do this is to imagine a series of FRII HERGs forming at different times, producing a separation between otherwise similar paths. In other words, we have combined, side-by-side, paths like those of Fig. 3 and simply shifted them along the x-axis, producing multiple plots of translated but equal configurations. Since supermassive black hole mass increases in time due to accretion, from a qualitative perspective, similar information appears on both a time and black hole mass plot despite a relative stretching between such diagrams due to short lifetimes and smaller mass increase during the retrograde phase compared to the prograde one. In other words, one can produce a qualitatively valid diagram by exchanging time with black hole mass. Finally, via the black hole mass-galaxy luminosity relation, one can exchange black hole mass with optical galaxy luminosity on the x-axis. These steps constitute a qualitative, zeroth-order attempt, at illustrating the consequences of our model on the evolution of a $family$ of powerful radio-loud objects. The result is Figure 7. From a qualitative perspective, then, the Ledlow-Owen diagram marks a division between objects that are young and powerful and others that are old and weak. Although that is the general trend, near the transition region of Figure 3, we can appreciate the existence of FRIIs that have weaker jets compared to FRIs further up beyond the break in the prograde regime.

The presence of a large population of FRIIs (blue) in the lower part of Figure 7 as opposed to the actual Owen-Ledlow diagram is simplistic in two ways. First, the diagram fails to capture the fact that the lower power FRII engines are less collimated than their more powerful counterparts suggesting a less superficial classification in which "FRII-like" or "blue-like" objects populate the lower regions of Figure 7. Second, we must also consider the effects of the external environment. As galaxy luminosity increases to the right on the x-axis, the galactic environment is more prone to turning these otherwise low power FRIIs into FRIs. Applying the same argument to the FRIIs (blue) that are mixed in with the FRIs (red) further up but to the right in the diagram of Figure 7 (i.e. where the objects are living in more dense stellar environments compared to their counterparts at equal jet power further back along the x-axis) suggests that environment might be responsible for turning some of them into FRIs. In other words, the further to the right we move on the diagram, the further up in the vertical direction we expect to replace FRIIs with FRIs. Because, to re-emphasize, our theoretical paths of Figure 7 are based solely on the properties of the jet engine, it is not surprising that it is precisely that which we are not modeling (i.e. environment) that is required to make theory compatible with observation. In other words, the Fanaroff-Riley dichotomy remains a function of jet power (governed by black hole spin) and environmental factors. We recognize that producing Figure 7 does not yield additional predictive power. However, we suggest that the simple compatibility at even a superficial level between the gap paradigm and the actual Owen-Ledlow diagram is statistically non-trivial.

3.5 Fe Kα Lines and Disk Winds

One interpretation of the narrowness of iron lines in HERGs compared to radio-quiet AGN is that the innermost stable circular orbit is further away from the black hole for higher retrograde accretion systems (we will suggest that true radio-quiet AGN are maximally spinning prograde systems). As far as reflection features in the inner disk regions go, even mild relativistic motion in coronal material above an accretion disk can reduce the reprocessed radiation from the disk (Beloborodov 1999). At velocities of just under $0.3c$, fluorescent line emission is effectively washed out (Reynolds & Fabian 1997). Therefore, the weakness of reflection features in HERGs may simply be the natural consequence of highly relativistic motion away from the disk in the inner regions where both BZ and BP conspire to produce relativistic jets while their narrowness indicates disk inner edges at larger radii.

The largeness of the gap region that produces the powerful, collimated jets of the FRII HERGs is also associated with an absence of inner-disk regions that are close to the black hole where gravitational potential energy can be reprocessed in the disk. As mentioned above, the absence of this reservoir of gravitational energy is compatible with a decrease or absence of disk winds further out in the disk. FRI LERGs, on the other hand, also fail to produce disk winds but due to the fact that the flow is advective dominated and not thin-disk-like. FRI HERGs, according to our model, should possess disk winds because the flow is thin-disk-like and the gap region is smaller so the reservoir of reprocessable gravitational energy near the black hole for use further out in the disk is comparatively larger. We will argue, however, that as the spin increases in the prograde direction, the increase in disk winds resulting from smaller ISCO radii, inhibit jets, so that FRI HERGs fails to be appropriate nomenclature once jets are absent. As a result, FRI HERGs applies only to lower prograde HERGs.

The fact that FRI LERGs are located on the right-hand side of Figure 3 implies that such objects should display a weak dependence on black hole spin since the power is roughly a flat function of spin for a range of intermediate spins. As pointed out (Garofalo 2009b), this alleviates the fine-tuning issue of Nemmen et al (2007) and Benson & Babul (2009). In addition, the retrograde or FRII region involves a much steeper function of black hole spin so the dependence on accretion rate should not be the same as it is for the FRIs. In other words, our model removes the need for even higher accretion rates in order to model the most powerful FRIIs, i.e. radio-loud quasars. It might be worth emphasizing that although jet power in the BZ effect does not come from the accretion power per se, the magnetic field which allows extraction of black hole rotational energy depends on the accretion rate in such a way that for fixed black hole spin, BZ power depends linearly on

accretion rate in ADAFs. We also point out that retrograde accretion states are short-lived. From purely accretion considerations, a highly-spinning retrograde black hole will be spun down to zero spin when the black hole has accreted about 0.2 of its original mass (Moderski & Sikora 1996). The prograde evolution regime, on the other hand, is slower not only because the black hole must reach a mass of $\sim 2.5M$ where M is the original black hole mass (Volonteri, Sikora & Lasota 2007), but also because the FRI regime is characterized by low angular momentum black hole-feeding in radiatively inefficient accretion. While FRIs have lifetimes reaching $\sim 10^8 years$, FRII lifetimes are about a factor of ten smaller at a few times ($10^6 - 10^7$) years (O'Dea et al. 2009).

4 DISCUSSION AND CONCLUSION

We presented a framework for the cosmological evolution of radio-loud galaxies in which the gap region between accretion disks and black holes is key. In this gap paradigm, jet production is most effective when black hole magnetospheres conspire with their large gap regions to produce strong black hole-threading magnetic fields that are geometrically favorable to both the BZ and BP effects. As time evolution through accretion spins the black hole up in the prograde direction and the gap region size decreases, the interaction of rotating black holes with their magnetospheres becomes inefficient and jets weaken, become less collimated and if accretion spins the black hole up to high prograde values, likely fails entirely to produce jets. Maximally spinning prograde black hole magnetospheres that are the result of cosmological evolution via accretion, thus, may be systems that have now become inactive. The radio-quiet quasars formed in ellipticals may, instead, involve the population of post-merger systems characterized by high accretion onto spinning black holes in a prograde configuration. According to our scenario, the origin of the radio-loud/radio-quiet dichotomy may lie in the existence of two types of engine efficiencies. On the one hand, retrograde black holes conspiring with their magnetized flows are highly efficient in producing non-thermal, jet outflows, but shorter-lived configurations. These engines produce the observed radio-loud population. On the other hand, prograde, high accretion systems with small gap regions, while incapable of producing powerful jets, are capable of tapping into the gravitational potential energy of their inner accretion flow, making them highly efficient in producing strong thermal emission. The reprocessed gravitational potential energy of the inner regions near the rapidly spinning black hole is fundamental in producing the disk winds from larger disk radii. It has recently been shown that GRS 1915+105, a galactic microquasar, exhibits a soft state in which the radiation field drives a hot wind off the accretion disk carrying enough mass to halt the flow of matter into the radio jet (Neilsen & Lee 2009), a picture that is underscored by theoretical work (Meier 1996) and for which observation is mounting in other systems as well (Blum et al. 2010). This scenario suggests that most FRI HERGs are systems in which the disk winds eventually inhibit jet production making such objects part of the radio-quiet population, thereby explaining the rarity of FRI HERGs. The handful of observed FRI HERGs are then systems where the black hole spin is small, producing relatively larger gap regions, which decreases the production of winds further out from the disk and allows the presence of an FRI jet. In other words, in the cosmological evolution of radio-loud objects, FRI HERGs are objects that are transitioning away from strong jet production and weak winds, to a scenario involving weaker jets and stronger winds but that have not reached the high prograde spin states that would produce strongest winds and weakest or no jets. We highlight the compatibility of this scenario with the existence of FRI type radio quasars (Heywood et al 2007) as pointed out to us by David L. Meier. The fact that accretion states transition from HERGs to LERGs, however, allows such systems to remain radio-loud as they increase their prograde spins as a result of the failure of ADAFs to produce the strong jet-inhibiting disk winds. Thus, spinning black holes produce both FRII HERGs and radio-quiet quasars depending on retrograde vs prograde accretion.

If mergers are responsible for both the high accretion rates and the occurrence of retrograde flows, it does not surprise that spiral galaxies are not competitive in their radio-loudness, and less accretion powered than the post-merger ellipticals. If retrograde accretion is formed in mergers, it also does not suprise that spirals are predominantly radio-quiet. In fact, only the low prograde spin configurations would lead to radio-loudness. Given that higher prograde accretion systems surrounded by radiatively efficient thin disks have smallest gap regions and the strongest jet-inhibiting winds, higher prograde spin systems in spirals should be radio-quiet; and, therefore, maximally spinning prograde configurations should be the most radio-quiet sources. In short, prograde vs retrograde, radiatively efficient accretion flows, produce the radio-quiet/radio-loud dichotomy.

And finally, we conclude our discussion with a glance at the implications for microquasars. Because such objects are prograde accretion systems, their accretion state changes produce the microquasar counterpart to AGN HERGs and LERGs, or more appropriately, a transition between high prograde spin, high excitation accretion states (or radiatively efficient accretion states) to high prograde spin, low excitation accretion states (or radiatively inefficient accretion states). If the parallel with the FRII feedback phase in AGN is valid, these high prograde spin, high excitation accretion states in microquasars produce strong disk winds that expel the gas (Neilsen & Lee 2009), thereby producing an ADAF phase during which disk winds drop and jets are no longer hindered while the system enters the radio dominated hard state. Eventually, the accretion flow from the companion allows the system to re-enter the soft or radiatively efficient accretion state. The extension of our model to microquasars suggests that the approach to the high excitation accretion (soft) state from the low excitation accretion (hard) state, involves the brief combined presence of a BZ component and a BP-like component produced by the onset of inner disk winds. In other words, there is a short time during which the microquasar mimicks the conditions in FRII HERGs, thereby producing a powerful, collimated jet. Note that no spin change occurs. This suggests that microquasars undergo state transitions that take them from high prograde spinning high excitation accretion states (soft states) to high prograde spinning low excitation accretion states (hard states) and back, and that during the low excitation to high excitation transition, the physical conditions of an FRII HERG are briefly produced.

We summarize our main conclusions as follows:

(i) FRIIs have retrograde spin while FRIs have prograde spin

(ii) FRII HERGs evolve toward FRI LERGs

(iii) FRIIs have larger jet efficiencies while FRIs have lower jet efficiencies

(iv) High prograde spin systems in HERG states have large disk efficiencies (and thus strong disk winds) while LERG states and retrograde accretion states have lower disk efficiencies (and thus lower disk winds)

(v) Highly efficient jet engines are highly inefficient disk engines and viceversa

(vi) FRI HERGs have low prograde spin

(vii) Radio quiet AGN are high spinning prograde, radiatively efficient systems

(viii) Maximally spinning prograde, radiatively efficient systems, are the most radio quiet AGN

(ix) Spiral galaxies involve prograde accretion

(x) Spiral galaxies should be more radio loud when the spin is lower and more radio quiet, quasar-like, when the spin is high

(xi) A radiatively inefficient to radiatively efficient transition, in high prograde systems, produces a short-lived, powerful, collimated jet as observed in microquasars.

We conclude by highlighting the fundamental role or impact of general relativity in galaxy evolution in this model. The validity of our paradigm suggests that aspects of the spacetime metric that are assumed to govern physics in regions provincially relegated to the near black hole, are in fact dominant on much larger scales, to the extent that galaxy morphology, energetics, and evolution, are tightly linked to the details of strong-field general relativistic effects. Whereas a Newtonian treatment of spacetime is successful just a few gravitational radii from the black hole in the sense that relativistic corrections are negligible there, the scale of influence of black hole spin that our paradigm forces us to grapple with is daunting, with up to more than eight orders of magnitude beyond its local sphere of influence. It is the details of tiny regions of highly curved spacetime that have the greatest effect on the large-scale properties of galaxies.

5 ACKNOWLEDGMENTS

D.G. thanks David L. Meier for discussion on the FRI/FRII division, the physics of jet launching, propagation and collimation, and for commenting on the draft as a whole, Peter Polko for stimulating ideas on the effects of BP jets on accretion disk coronae, Christopher S. Reynolds for issues concerning broad iron lines and jet energetics and Cole Miller and Marta Volonteri for discussion on retrograde accretion. We acknowledge the role of and thank the three referees and three editors that were involved in this project. The research described in this paper was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration. D.G. is supported by the NASA Postdoctoral Program at NASA JPL administered by Oak Ridge Associated Universities through contract with NASA.

REFERENCES

Allen S.W. et al, MNRAS, 2006, 372, 21
Antonuccio-Delogu V. & Silk J., 2010, MNRAS, submitted
Arshakian, T., Beck, R., Krause, M., Sokoloff, D., & Stepanov, R., Proceedings to Panoramic Radio Astronomy, Groningen, 2009
Barnes J.E.& Hernquist, L. 1991, ApJ, 370, L65
Baum S.S., Zirbel E.L. & O'Dea C.P., 1995, ApJ, 451, 88
Beloborodov, A.M., 1999, ApJ, 510, L123
Benson A.J. & Babul A., 2009, MNRAS, 397, 1302
Bicknell G.V., 1995, ApJS, 101, 29
Blandford, R. D., & Payne, D. G. 1982, MNRAS, 199, 883
Blandford, R. D., & Znajek, R. L. 1977, MNRAS, 179, 433
Blandford, R.D., in Active Galactic Nuclei, ed. T.J.-L. Courvoisier & M. Mayor, 161-275
Blum J.L. et al, 2010, ApJ, in press
Bogovalov, S. & Tsinganos, K. 2005, MNRAS, 357, 918
Brenneman, L., & Reynolds, C.S., 2006, ApJ, 652, 1028
Bridle A.H. et al, 1989, AJ, 97, 674
Cao X., 2003, ApJ, 599, 147
Daly, R.A., ApJ, 2009, 691, L72
Daly, R.A., ApJ, 2009, 696, L32
De Young D.S., 1993, ApJ, 405, L13
Donato D., Sambruna, R.M., Gliozzi, M, 2004, ApJ, 617, 915
Evans, D., 2004, ApJ, 612, 786
Evans, D., et al, 2006, ApJ, 642, 96
Fabian, A.C. et al, Nature, 2009, 459, 540
Fanaroff, B.L.& Riley, J.M., 1974, MNRAS, 167, 31P
Ferrarese, L., & Merritt, D., 2000, ApJ, 539, L9
Garofalo, D., 2009, ApJ, 699, L52 (a)
Garofalo, D., 2009, ApJ, 699, 400 (b)
Gebhardt, K., et al. 2000, ApJ, 539, L13
Ghisellini G., Celotti A., 2001, A&A, 379, L1
Gopal-Krishna & Wiita P.J, 2000, A&A, 363, 507
Grandi P., Urry C.M., Maraschi L., 2002, NewAR, 46, 221
Kormendy, J., & Richstone, D., 1995, ARA&A, 33, 581
Hardee P.E & Hughes P.A., 2003, ApJ, 583, 116
Hardcastle M.J., Evans D.A. & Croston J.H., 2006, MNRAS, 370, 1893
Hardcastle M.J., Evans D.A. & Croston J.H., 2007, MNRAS, 376, 1849
Heywood I., Blundell K.M.& Rawlings S., 2007, MNRAS, 381, 1093
Hughes, S.A. & Blandford, R.D., 2003, ApJ, 585, L101
Kaiser C.R. & Alexander P., MNRAS, 1997, 286, 215
King A.R., Lubow S.H., Ogilvie G.I. & Pringle J.E., 2005, MNRAS, 363, 49
King, A.R., Pringle,J.E. & Hofmann, J.A., 2008, MNRAS, 385, 1621
Kormendy, J., & Richstone, D., 1995, ARA&A, 33, 581
Kuncic, Z. & Bicknell, G.V., 2004, ApJ, 616, 669
Kuncic, Z. & Bicknell, G.V., 2007, Ap&SS,311, 127
Laing R.A., 1994, ASPC, 54, 227
Lal et al, in preparation
Livio, M., Ogilvie, G.I. & Pringle, J.E., 1999, ApJ, 512, 100
Magorrian, J., et al. 1998, AJ, 115, 2285
Mangalam A., Gopal-Krishna & Wiita P.J., 2009, MNRAS, 397, 2216
Marchesini D., Celotti A. & Ferrarese L., 2004, MNRAS, 351, 733
Marconi, A., & Hunt, L.K., 2003, ApJ, 589, L21
McKinney J.C. & Narayan R. 2007, MNRAS, 375, 513
McKinney J.C. & Blandford R.D., 2009, MNRAS, 394, L126
McKinney J.C. & Gammie C.F., 2004, ApJ, 611, 977
McNamara B.R., et al,2009, ApJ, 698, 594
Menon, G. & Dermer, C.D., 2005, ApJ, 635, 1197
Meier D. L., 1999, ApJ, 522, 753
Meier D.L. et al., Science 291 (2001), 84
Meier D.L., 1996, ApJ, 459, 185
Miller, M.C., 2002, ApJ, 581, 438
Moderski R.& Sikora M., 1996, A&AS, 120, C591
Moderski R., Sikora M.& Lasota J.-P., MNRAS, 1998, 301, 142
Nakamura, M. & Meier, D.L., 2004, ApJ, 617, 123
McClintock, J.E., Shafee, R., Narayan, R., Remillard, R.A., Davis, S.W.& Xin-Li, L., ApJ, 652, 518
Narayan, R. & Yi I., 1995, ApJ, 452, 710

Neilsen J. & Lee J., Nature, 458, 481
Neemen R.S. et al, 2007, MNRAS, 377, 1652
Nesvadba N.P.H, Lehnert M.D., De Breuck C., Gilbert A. & van Breugel W., 2008, A&A, 491, 407
Novikov I. & Thorne K., 1973, Black Holes (Les astres occlus), p. 343
O'Dea et al, 2009, A&A, 494, 471
Ogle P., Whysong D. & Antonucci R., 2006, ApJ, 647, 161
Rees M.J., 1982, IAUS, 97, 211
Reeves J.N.& Turner M.J.L., 2000, MNRAS, 316, 234
Reeves J.N., Sambruna R.M., Braito V. & Eracleous M., 2009, ApJ, 702, L187
Reynolds C.S. et al, 1996, MNRAS, 283, L111
Reynolds C.S. & Fabian A.C. 1997, MNRAS, 290, L1
Reynolds C.S., Garofalo D.& Begelman M.C., 2006, ApJ, 651, 1023
Sambruna et al, 2009, ApJ, 700, 1473
Smolcic V., 2009, ApJ, 699, L43
Smolcic V. et al, 2009, ApJ, 696, 24
Tchekhovskoy A., McKinney J.C. & Narayan R. 2009, ApJ, 699, 1789
Tchekhovskoy A., Narayan R & McKinney J.C. 2010, ApJ, in press
Thorne K.S., Price R.H. & Macdonald D.A., 1986, Black Holes: The Membrane Paradigm (New Haven: Yale Univ. Press)
Tremaine S., et al 2002, ApJ, 574, 740
Volonteri M., Sikora M., & Lasota J-P, 2007, ApJ, 667, 704
Wilms J. et al, 2001, MNRAS, 328, L27
Wilson A.S. & Colbert E.J.M, 1995, ApJ, 438, 62
Zoghbi A. et al, 2010, MNRAS, 401, 2419

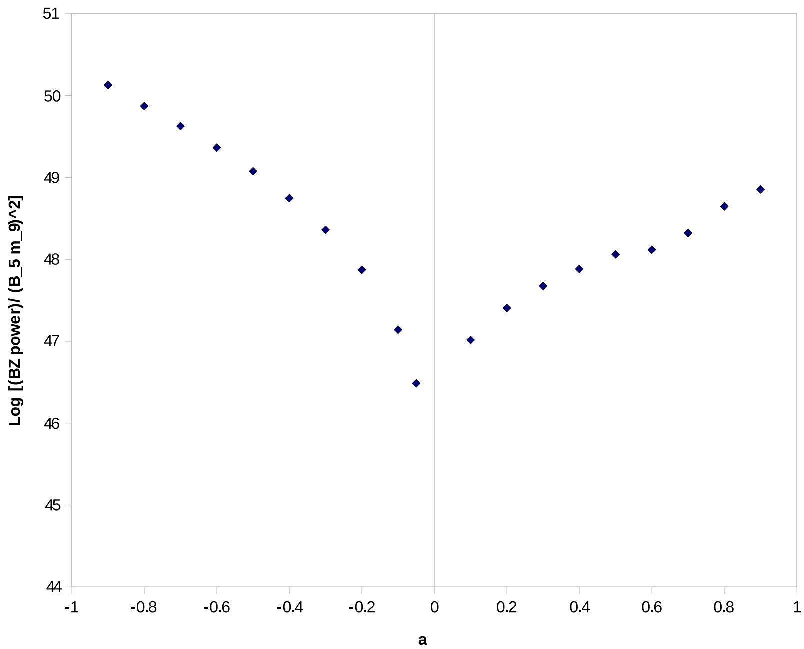

Figure 1. The BZ power vs spin accretion state (negative for retrograde and positive for prograde).

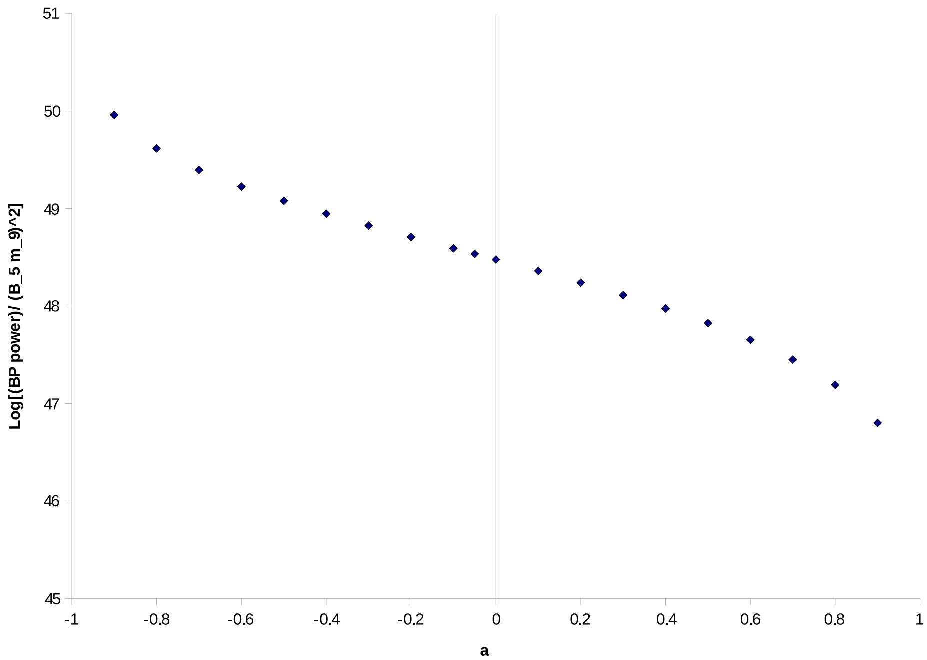

Figure 2. The BP power vs spin accretion state (negative for retrograde and positive for prograde).

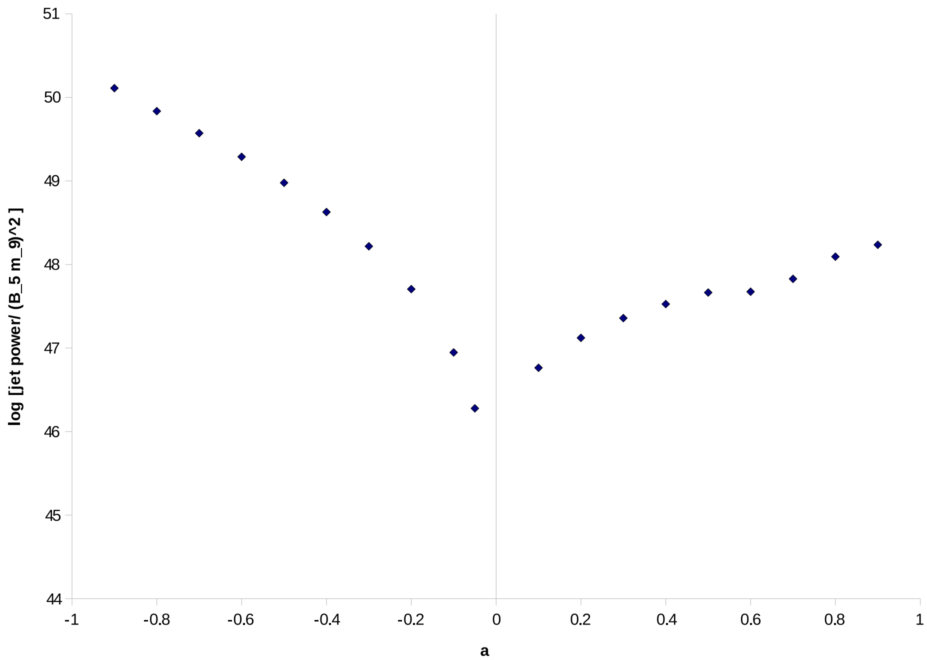

Figure 3. The overall jet power assuming BZ and BP operate in tandem via equation 20. B_5 is magnetic field in units of 10^5 Gauss and m is the ratio of black hole mass to 10^9 solar masses (i.e. for a 10^5 Gauss field, a 10^9 solar mass black hole, and a retrograde spin of -0.9, the power is slightly above 10^{50} erg/s). The value of δ is at a conservative estimate of about 2.5 but could be a magnitude or more higher. Numerical simulations of jets are needed to determine this value precisely. We emphasize that the discussion in section 4 implies that the above jet power dependence becomes irrelevant at high prograde spin in HERGs since the efficiency shifts from jets to disks.

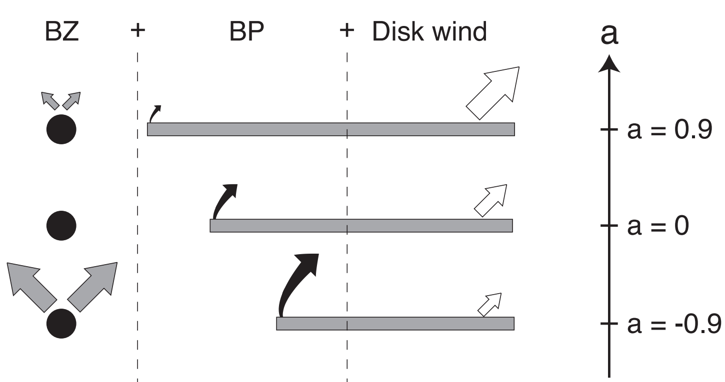

Figure 4. Left column: Despite a small gap region, high prograde spinning systems (upper panel) still produce BZ jets because the spin is large, but they are weaker than for high retrograde systems where the gap region is larger (lower panel). Center column: The increased size of the gap region as the black hole spin goes from high prograde (upper panel) toward high retrograde (lower panel) makes the BP jets stronger as indicated by the length of the arrows originating in the accretion disk. However, as discussed in Section 4, this BP efficiency may become negligible at high prograde spin (Neilsen & Lee 2009). Right column: The increased size of the gap region for higher retrograde systems produces weaker disk winds due to the decrease in the amount of reprocessable gravitational potential energy near the black hole.

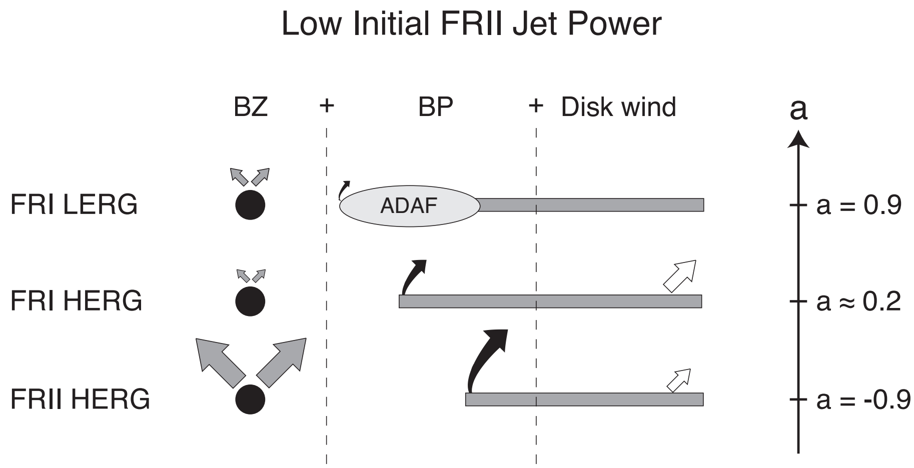

Figure 5. The evolution in time of lower power FRIIs, less able to expel the cold gas, thereby accreting in the cold gas phase for prolonged periods and thus into the prograde spin regime as HERGs. Time increases upward.

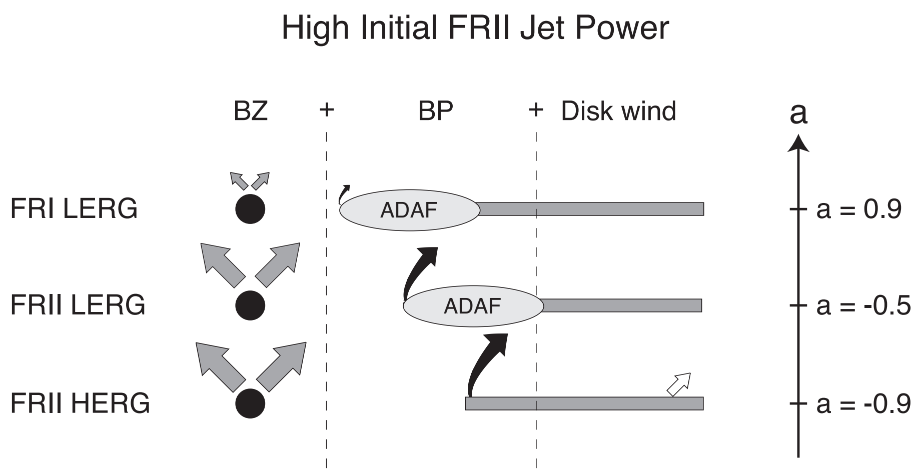

Figure 6. The evolution in time of higher power FRIIs, more able to expel the cold gas, thereby accreting already in the ADAF phase while still in the retrograde regime. Time increases upward.

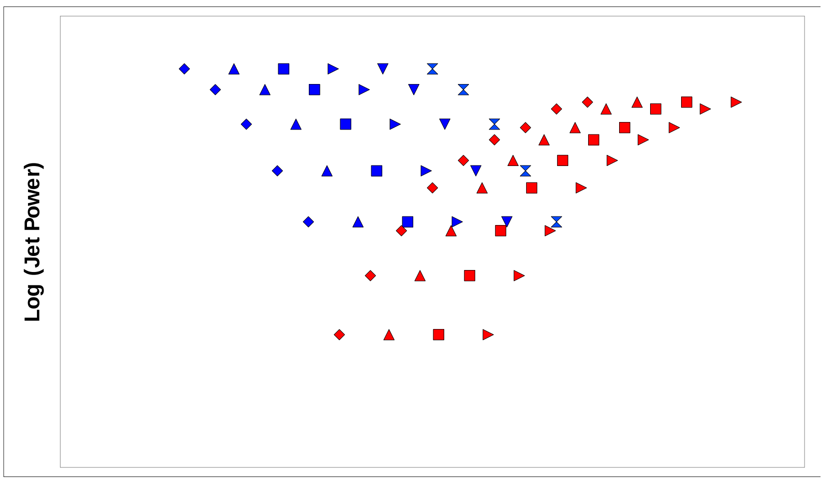

Figure 7. Going from jet power vs spin state to the Ledlow-Owen diagram. The x-axis can have black hole mass, time or galaxy optical luminosity depending on the relative stretching between retrograde and prograde regimes. FRII diamonds (blue) evolve into FRI diamonds (red); FRII triangles (blue) evolve into FRI triangles (red); FRII squares (blue) evolve into FRI squares (red) etc. We have combined multiple theoretical evolutionary paths and have focused on the transition region between FRIIs (blue) and FRIs (red) at lower power (i.e. we have focused on the region of Figure 3 where spin varies between -0.2 and 0.2 and the y-axis is below unit 47).